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Comparative impact of four walnut based intercropping systems on soil physical properties and aggregate stability

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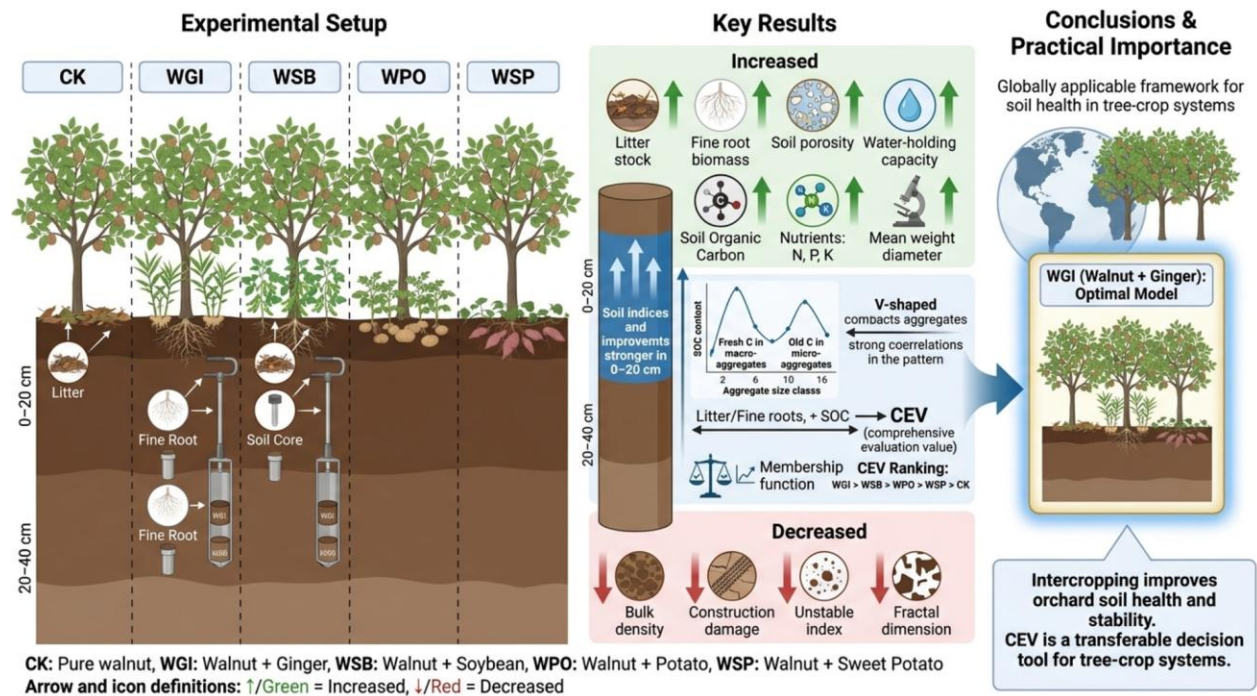
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Abstract:

Intercropping enhances soil properties and aggregate stability, serving as a key management practice for improving orchard productivity and land-use efficiency. This study investigated the impact of different intercropping models in a walnut plantation by planting ginger (WGI), sweet potato (WSP), soybean (WSB), and potato (WPO) on soil physical properties and aggregate stability as compared to the pure walnut (CK). Litter, fine root, and soil samples were collected to analyze the soil physicochemical properties and aggregate stability, and a membership function was used to estimate the intercropping models. All intercropping models increased litter stock, fine root biomass, soil porosity (including capillary porosity, non-capillary porosity, and total porosity), water-holding capacities (including natural water content, maximum water-holding capacity, capillary water-holding capacity, and field water-holding capacity), >0.25 mm water-sieved aggregate, soil organic carbon (SOC), and nutrients (including total nitrogen, alkali-hydrolysable nitrogen, available phosphorous, and available potassium) content, and mean weight diameter; decreased bulk density, percent of construction damage, unstable index, and fractal dimension. These soil indices in the 0–20 cm layer were superior to those in the 20–40 cm layer. The SOC

content showed a “V” trend with the change of aggregate particle size. Comprehensive evaluation value (CEV) was significantly different ($P < 0.05$) among the models, ranking as WGI > WSB > WPO > WSP > CK. Both litter stock and fine root biomass significantly ($P < 0.01$) correlate with SOC and CEV, and CEV significantly ($P < 0.05$ or $P < 0.01$) correlates with all determined indices. Among the tested models, WGI showed the greatest improvements in soil physical properties and aggregate stability under the conditions of this study.. These findings provide a preliminary framework for evaluating soil health in walnut-based intercropping systems under subtropical monsoon climates. However, the CEV approach should be validated across broader edaphoclimatic conditions before wider application.

Keywords: Aggregate stability, Intercropping, Soil organic carbon, Soil physical properties, Soil porosity, Walnut plantation



1. Introduction

The global agricultural sector faces mounting pressure from rapid population growth and climate change, necessitating sustainable intensification strategies to ensure food security (Silva et al.,

2025). Among these strategies, diversified cropping systems such as agroforestry and intercropping have gained increasing attention worldwide for their potential to enhance land-use efficiency, improve soil health, and sustain productivity under limited resource conditions. By integrating perennial and annual crops within the same system, intercropping offers opportunities to optimize spatial and temporal resource utilization while maintaining ecological stability.

Walnut (*Juglans regia* L.) is a high-value crop widely cultivated in China, the world's leading producer. Beyond China, walnut is cultivated across diverse climatic zones globally, including Mediterranean Europe, California (USA), Chile, and Australia, making sustainable management practices in walnut systems relevant to multiple regions worldwide. To optimize land-use efficiency and economic returns during the early stages of walnut establishment, intercropping has been widely adopted. This practice is known to enhance soil quality and sustain productivity by increasing soil organic matter, nutrient availability, and enzyme activity compared to monocropping systems (Bai et al., 2022; Brooker et al., 2015).

In this context, intercropping has emerged as a key practice to boost yields on limited arable land (Wu et al., 2021). While extensive research has documented the benefits of intercropping on soil chemical and biological properties such as fertility and microbial diversity in walnut orchards (Dang et al., 2020), its impact on soil physical properties particularly the mechanistic links between root inputs, aggregate formation, and carbon stabilization remains comparatively underexplored across agroforestry systems globally. Understanding these mechanisms is essential for developing universally applicable management strategies for sustainable intensification.

Soil physical characteristics, including bulk density (BD), porosity, water-holding capacity (WHC), and aggregate stability, are critical determinants of root growth, water infiltration, and overall soil structure (Lal, 2015). These properties directly influence root system development, which in turn affects water and nutrient uptake, tree health, and yield (Neguşier et al., 2024). Although studies

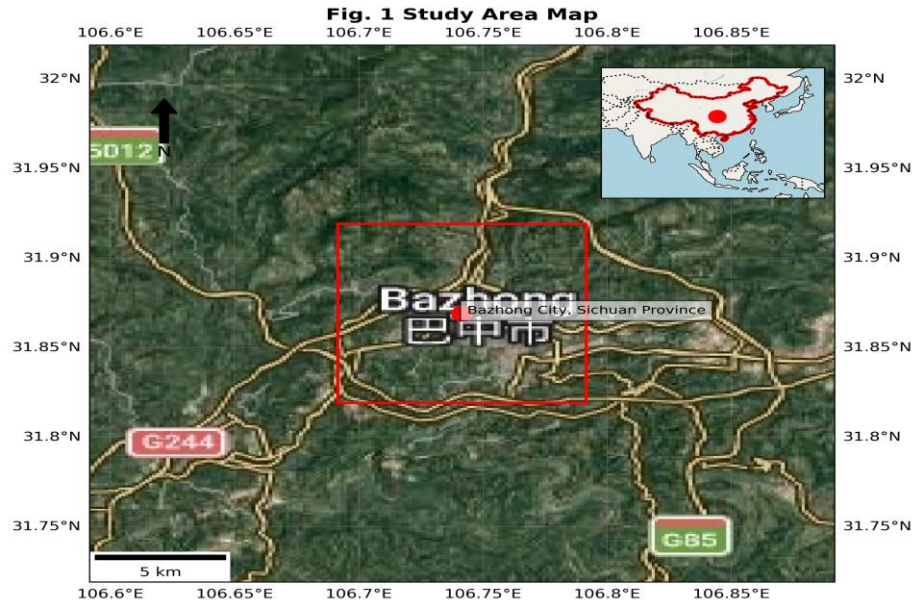
like Rinot et al. (2019) have primarily focused on chemical and biological indicators, they offer limited insight into these essential physical parameters. Similarly, while Xu et al. (2021) underscore the importance of soil physical health for sustained productivity, a detailed evaluation under various walnut intercropping configurations is still lacking. Furthermore, although root plasticity in response to intercropping has been observed (Cardinael et al., 2015), its interaction with modified soil physical conditions in the deeper soil layers is not well understood.

To address these gaps, using a walnut plantation as a model tree-crop system, this study aims to: (1) comprehensively evaluate the effects of different intercropping models on soil physical properties and aggregate stability; (2) identify the optimal intercropping system for enhancing soil health and land-use efficiency; and (3) propose a preliminary evaluation framework for soil health assessment in tree-crop systems, acknowledging that further testing is required under different environmental conditions.. By analyzing these key parameters, this research provides a scientific basis for selecting sustainable agroforestry practices that improve soil quality and support the development of site-specific management strategies for tree-crop systems in similar agroecological regions.

2. Materials and methods

2.1. Overview of the study area

The experimental site is located in a walnut cultivation demonstration area (106°06'E, 31°57'N), at an altitude of 682–770 m with slopes ranging from 15° to 21°. The region experiences a subtropical monsoon climate. The study site is located at 106°06'E, 31°57'N, as indicated in Fig. 1.



The study area is representative of typical walnut-growing environments and comparable to agroforestry systems in different parts of the world, exhibiting soil and topographic conditions common to agroforestry systems globally. Walnut (*Juglans regia*) trees were planted in the autumn of 2016 at a spacing of 4 m × 5 m, using the 'Qingxiang' walnut variety. The prior pot soil with physical and chemical properties as follows: Organic matter 22.3 g·kg⁻¹, total N 1.2 g·kg⁻¹, total P 0.027 g·kg⁻¹, total K 10.9 g·kg⁻¹, alkali-hydralysable N 87.5 mg·kg⁻¹, available P 11.8 mg·kg⁻¹, available K 135.8 mg·kg⁻¹, pH 4.57, sand 49.1%, silt 42.2%, and clay 8.7%. To improve the ecological and economic benefits of walnut plantation during the young growth stage, intercropping was initiated in the spring of 2017 to combine long-term and short-term benefits. Intercropping crops planted under the walnut plantation, including soybean, potato, ginger, and sweet potato, with pure walnut plantations as a control (CK). The density of *Zingiber officinale*, *Ipomoea batatas*, *Glycine max*, and *Solanum tuberosum* was 80000, 55000, 160000, and 64000 plants ha⁻¹, respectively. Four intercropping systems were developed: walnut + ginger (WGI), walnut + sweet potato (WSP), walnut + soybean (WSB), and walnut + potato (WPO). Fertilizer

application followed standard local practices for each treatment. All other management (irrigation, weeding, pest control) was kept standard across all treatments.

2.2. Experimental methods

The experiment was established as a randomized complete block design (RCBD) to account for potential field variability. The study comprised five treatments: four walnut intercropping models (WGI, WSP, WSB, WPO) and a pure walnut control (CK). The experiment was replicated three times, with each replication representing a block defined by similar slope aspect, gradient, position, and elevation. In October 2022, three 10 m × 10 m standard plots (blocks) were established. Within each block, the five treatments were randomly assigned to individual plots. From each treatment plot, litter, fine root, and soil samples were collected from five randomly selected sampling points. Samples from the five points within the same plot and soil depth (0–20 cm and 20–40 cm) were combined each soil depth samples to form a single composite sample (Gong et al., 2008; Lv et al., 2022). This sampling protocol yielded three true replicates per treatment per depth for all subsequent laboratory analyses.

2.3. Soil, litter, and fine root sampling

Quarterly sampling of soil, fine root, and litter was conducted throughout the study period. The initial sampling round was carried out in October 2022, and the data presented in this study are from this first sampling event. Within each plot, samples were taken from the 0–20 cm and 20–40 cm soil depths. Litter was collected directly from the soil surface. For soil sampling, a core sampler was used to collect undisturbed soil cores for bulk density and porosity analysis, while additional soil was collected for aggregate stability and chemical analysis. Visible fine roots were manually picked from the soil samples. The remaining roots were recovered by washing the soil over a sieve. All litter and fine root samples were oven-dried at 80 °C to a constant weight to determine stock and biomass. Soil samples for chemical analysis were air-dried after being gently broken to pass

through a 1 cm sieve. In contrast, soil for aggregate stability analysis was air-dried at room temperature with minimal disturbance to preserve the natural soil structure before dry and wet sieving. Soil BD, porosity composition, and water-holding capacity were determined by the ring method (Dai et al., 2021). All water-holding capacity values (natural water content, maximum water-holding capacity, capillary water-holding capacity, and field water-holding capacity) are expressed as percentages on an oven-dry soil weight basis (g water per 100 g dry soil). These values are consistent with previous studies using the same ring method and are not volumetric measurements. The dry-sieved aggregate (DSA) and wet-sieved aggregate (WSA) were determined by the machine-sieved method (Standards Press of China, 1998). Mean weight diameter (MWD), percent of construction damage (PCD), and unstable aggregate index (UAI) were calculated according to aggregate composition (Gong et al., 2009). Fractal dimension (FD) was calculated by the fractal model (Gong et al., 2007). SOC content was measured by the wet oxidation method at a temperature of 170 °C to 180 °C (Xu et al. 2020). Alkali-hydrolysable nitrogen (AHN), available phosphorus (AVP), and available potassium (AVK) content was determined by alkaline hydrolysis diffusion, Bray-P, and flame photometry method, respectively (Gong et al., 2012; Wang et al., 2015).

2.4. Statistical analysis

Excel 2016 and SPSS 26 were used for data processing and statistical analysis; Origin 2018 was employed for graphical representations. One-way ANOVA was applied to compare the means of indices. Pearson correlation analysis quantified relationships among the indices with significance set at 0.05 and 0.01 levels. For a comprehensive evaluation, the measured indices were divided into four groups. Indices in the first group (including litter stock and fine root biomass), the second group (including bulk density, non-capillary porosity, capillary porosity, natural water-

holding capacity, capillary water-holding capacity, maximum water-holding capacity, and field water-holding capacity), the third group (including SOC, TN, AHN, AVP, and AVK), and the fourth group (including MWD, >0.25 mm water-stable aggregate, FD, PCD, and UAI) were selected to calculate subordinate degrees. The formulas for those indices to calculate subordinate degree were $X(u) = (X - X_{\min}) / (X_{\max} - X_{\min})$ and $X(u) = 1 - (X - X_{\min}) / (X_{\max} - X_{\min})$; BD, FD, PCD, and UAI used the latter formula to calculate subordinate degree due to those indices negative correlated with soil physical properties and aggregation stability, while the rest indices used the former formula to calculate subordinate degree. Comprehensive evaluation value (CEV) is the total value of the average subordinate degree in each group. The higher CEV represents better improvement to soil physical properties and aggregate stability. All data were expressed based on oven-dry weight and mean with standard deviation.

3. Results

3.1. Litter stock and fine root biomass

Litter stock was significantly ($P < 0.05$) different among the intercropping models of walnut plantation. The WSB model showed the highest litter stock, while the CK was the lowest (Fig. 1). Litter stock ranked as WSB (1.25 Mg ha^{-1}) > WGI (1.15 Mg ha^{-1}) > WPO (1.14 Mg ha^{-1}) > WSP (1.10 Mg ha^{-1}) > CK (0.90 Mg ha^{-1}). Fine root biomass (FRB) varied significantly ($P < 0.05$) among the intercropping models of walnut plantation (Fig. 1b). The WGI model showed the highest fine root biomass (0.33 Mg ha^{-1}), while the CK had the lowest (0.08 Mg ha^{-1}) in 0–20 cm. Similarly, the WGI model maintained the highest fine root biomass (0.37 Mg ha^{-1}) and was significantly ($P < 0.05$) greater than other models in 20–40 cm. Fine root biomass ranked as WGI (0.70 Mg ha^{-1}) > WSB (0.63 Mg ha^{-1}) > WPO (0.44 Mg ha^{-1}) > WSP (0.39 Mg ha^{-1}) > CK (0.18 Mg ha^{-1}) in 0–40 cm. A significant correlation was found between FRB and SOC ($r = 0.76$, $P < 0.01$).

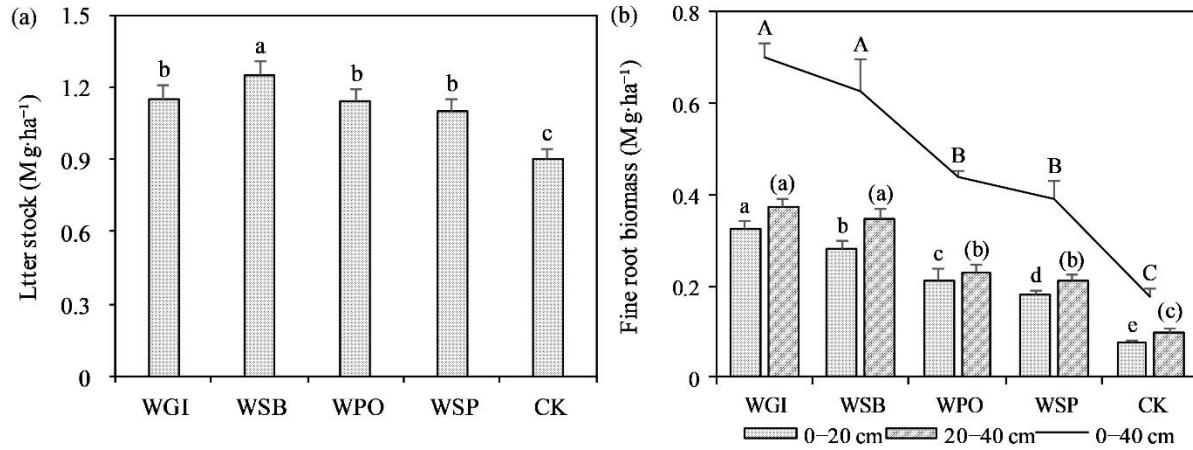


Fig. 1. Litter stock and fine root biomass (FRB) among the different intercropping models of walnut plantation. Bars with different letters (lower case for litter stock and FRB in the 0–20 cm layer; lower case in brackets for FRB in the 20–40 cm layer; upper case for FRB in the 0–40 cm layer) show significant differences at $P < 0.05$.

3.2. Soil bulk density and porosity

Soil bulk density was significantly ($P < 0.05$) affected by intercropping models (Fig. 2). The bulk density in the 0–40 cm layer decreased from 1.40 g cm^{-3} (CK) to 1.20 g cm^{-3} (WGI). The WGI model had a lower bulk density than the WSB, WPO, and WSP models. The bulk density of the WGI model in both 0–20 cm (1.09 g cm^{-3}) and 20–40 cm (1.31 g cm^{-3}) layers was the lowest.

Total porosity was significantly ($P < 0.05$) higher in intercropping systems than in the CK. The total porosity in the 0–40 cm layer increased from 41.1% (CK) to 50.8% (WGI). The WGI model showed higher total porosity than the WSB (46.4%), WPO (46.6%), and WSP (42.9%) models.

Capillary porosity and non-capillary porosity followed similar trends. The WGI model exhibited the highest capillary porosity (39.7%) and the WSB model showed the highest non-capillary porosity (11.7%) in the 0–40 cm layer. Correlation analysis revealed a strong negative relationship between bulk density and total porosity ($*r^* = -0.84$, $P < 0.01$), and a positive correlation between capillary porosity and total porosity ($*r^* = 0.81$, $P < 0.01$).

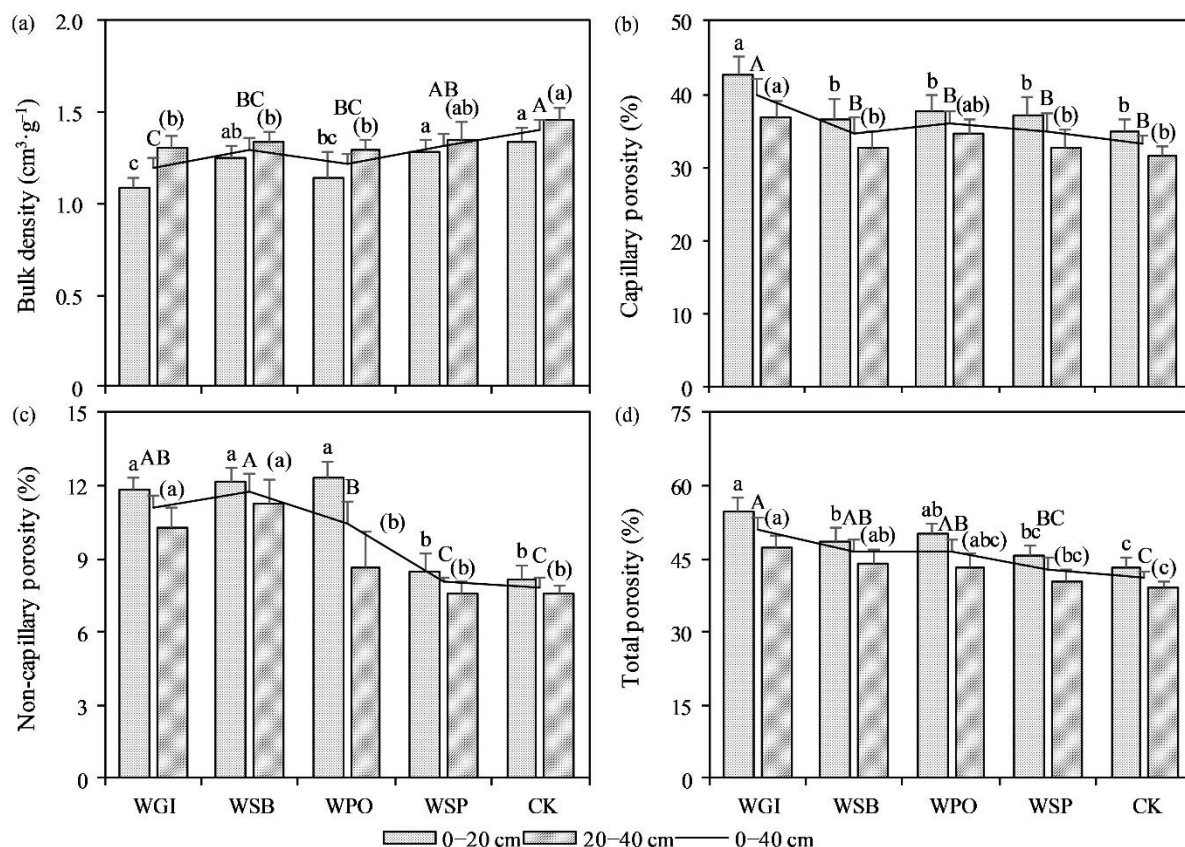


Fig. 2. Soil bulk density and porosities among the different intercropping models of walnut plantation. Bars with different letters (lower case for bulk density (BK), capillary porosity (CP), non-capillary porosity (NCP), and total porosity (TP) in the 0–20 cm layer; lower case in brackets for BK, CP, NCP, and TP in the 20–40 cm layer; upper case for BK, CP, NCP, and TP in the 0–40 cm layer) show significant differences at $P < 0.05$.

3.3. Soil water-holding capacity

Soil NWC, MWC, CWC, and FWC were significantly ($P < 0.05$) affected by intercropping systems (Fig. 3). The NWC in the 0–40 cm layer increased from 95.8% (CK) to 182.2% (WGI) among the models. The WGI model had a higher NWC than the WSB (110.2%), WPO (113.4%), and WSP (106.0%) models. The NWC of the WGI model (232.6%) in the 0–20 cm layer was significantly ($P < 0.05$) higher than that of the other models. MWC increased from 293.3% (CK) to 424.6% (WGI) in the 0–40 cm layer, with intermediate values for WSB (359.2%), WPO (383.0%), and WSP (326.2%). FWC followed the same trend, with the WGI model (303.8%) showing

significantly ($P < 0.05$) higher values than CK (201.7%) in the 0–40 cm layer. CWC ranked as WGI (229.7%) > WPO (226.8%) > WSB (213.8%) > WSP (200.3%) > CK (179.4%) in the 0–40 cm layer. The WGI model (306.3%) maintained significantly ($P < 0.05$) higher values in the 0–20 cm layer compared to other models. All WHC values are expressed on a dry-weight basis, consistent with the methodology described in Section 2.3.

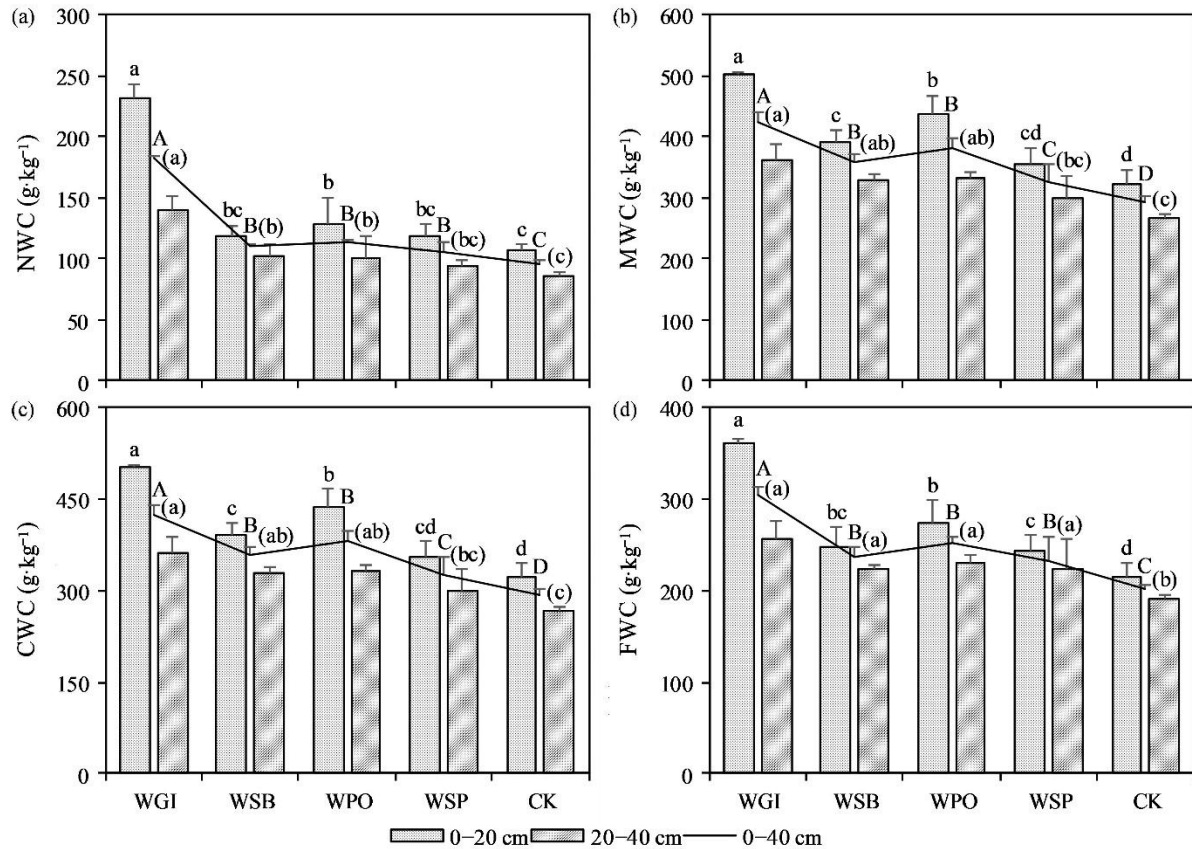


Fig. 3. Soil water-holding capacities among the different intercropping models of walnut plantation. Bars with different letters (lower case for natural water content (NWC), maximum water-holding capacity (MWC), capillary water-holding capacity (CWC), and field water-holding capacity (FWC) in the 0–20 cm layer; lower case in brackets for NWC, MWC, CWC, and FWC in the 20–40 cm layer; upper case for NWC, MWC, CWC, and FWC in the 0–40 cm layer) show significant differences at $P < 0.05$.

3.4. Soil aggregate composition and stability

212 DSA composition was significantly ($P < 0.05$) affected by the models (Fig. 4). The composition of
213 >5 mm aggregates in the 0–40 cm layer increased from 26.7% (CK) to 43.6% (WGI), with
214 intermediate values for WSB (41.2%), WPO (35.0%), and WSP (37.0%). The WGI model showed
215 the highest composition of >5 mm aggregates (50.0%), significantly greater ($P < 0.05$) than CK
216 (29.2%) in the 0–20 cm layer. Similarly, WGI maintained the highest proportion (38.3%) compared
217 to CK (24.4%) in the 20–40 cm layer. The composition of <0.25 mm aggregates showed the
218 opposite trend, decreasing from 20.1% (CK) to 6.1% (WGI) in the 0–40 cm layer. WSA
219 composition was significantly ($P < 0.05$) affected by the models. The composition of >5 mm WSA
220 in the 0–40 cm layer increased from 2.5% (CK) to 6.6% (WGI), with intermediate values for WSB
221 (4.8%), WPO (3.7%), and WSP (4.4%). WGI showed the highest composition of >5 mm WSA
222 (7.9%), significantly greater ($P < 0.05$) than CK (2.9%) in the 0–20 cm layer. Similarly, WGI
223 maintained the highest composition (5.5%) compared to CK (2.0%) in the 20–40 cm layer. The
224 composition of <0.25 mm WSA decreased from 76.7% (CK) to 57.3% (WGI) in the 0–40 cm layer.

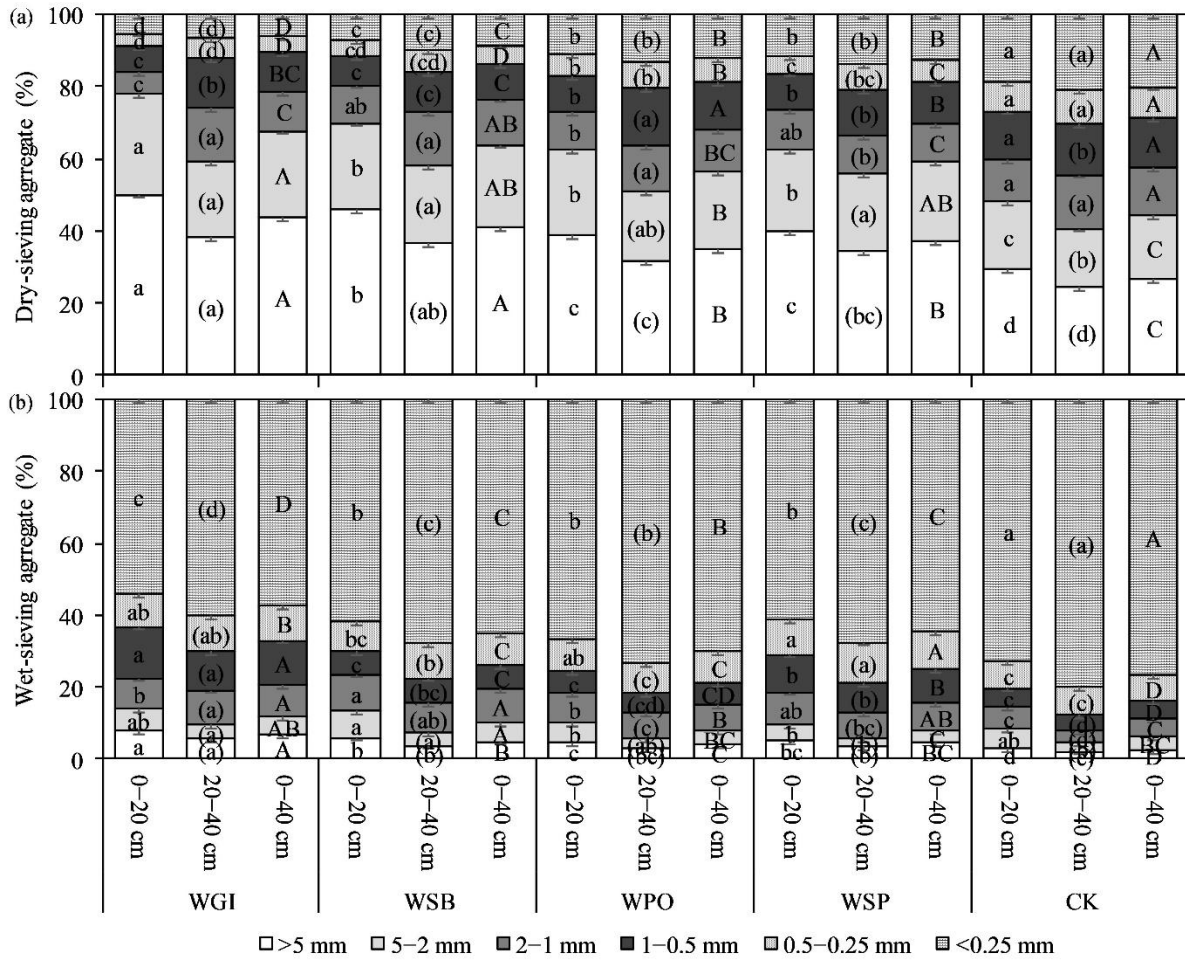


Fig. 4. Soil dry-sieving and wet-sieving aggregate composition among the different intercropping models of walnut plantation. Bars with different letters (lower case for the composition of the same particle-size aggregate (CSPA) under the same sieving condition in the 0–20 cm layer; lower case in brackets for CSPA under the same sieving condition in the 20–40 cm layer; upper case for CSPA under the same sieving condition in the 0–40 cm layer) show significant differences at $P < 0.05$.

3.5. Soil aggregate stability and fractal dimension

PCD in the 0–40 cm layer decreased from 70.8% (CK) to 54.5% (WGI), with intermediate values for WSB (61.7%), WPO (66.0%), and WSP (59.3%) (Fig. 5). WGI showed the lowest PCD (51.5%), significantly ($P < 0.05$) lower than CK (66.7%). UAI followed a similar trend, with WGI (80.0) showing a significantly ($P < 0.05$) lower value than CK (86.8) in the 0–40 cm layer. MWD

increased from 1.63 mm (CK) to 2.51 mm (WGI). FD values ranked as WGI (2.86) < WSB (2.88) < WPO (2.91) < WSP (2.89) < CK (2.93) in the 0–40 cm layer.

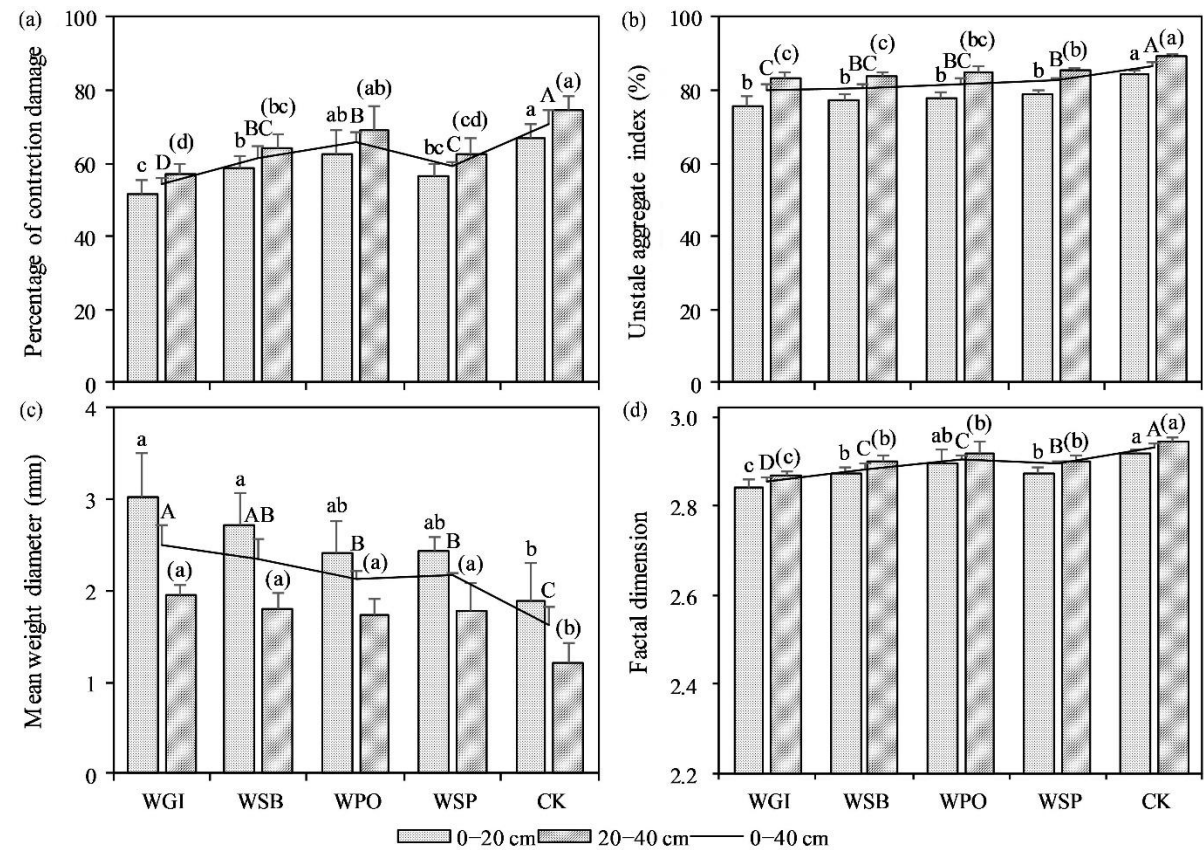


Fig. 5. Soil aggregate stability and fractal dimension among the different intercropping models of walnut plantation. Bars with different letters (lower case for percent of constitution damage (PCD), unstable aggregate index (UAI), mean weight diameter (MWD), and fractal dimension (FD) in the 0–20 cm layer; lower case in brackets for PCD, UAI, MWD, and FD in the 20–40 cm layer; upper case for PCD, UAI, MWD, and FD in the 0–40 cm layer) show significant differences at $P < 0.05$.

3.6. Aggregate particle-size soil organic carbon

Aggregate particle-size SOC content was significantly ($P < 0.05$) affected by the models (Fig. 6). The SOC content in >5 mm aggregate in the 0–40 cm layer increased from 12.6 g kg⁻¹ (CK) to 19.5 g kg⁻¹ (WGI), with intermediate values for WSB (18.2 g kg⁻¹), WPO (16.4 g kg⁻¹), and WSP (16.6 g kg⁻¹). WGI showed the highest SOC content in >5 mm aggregates (23.3 g kg⁻¹) in the 0–

20 cm layer, significantly ($P < 0.05$) greater than CK (14.6 g kg⁻¹). Similarly, WGI maintained the highest values (15.3 g kg⁻¹) compared to CK (9.7 g kg⁻¹) in the 20–40 cm layer. The SOC content in bulk soil followed the same trend, with WGI (18.7 g kg⁻¹) showing significantly ($P < 0.05$) higher values than CK (12.7 g kg⁻¹) in the 0–40 cm layer.

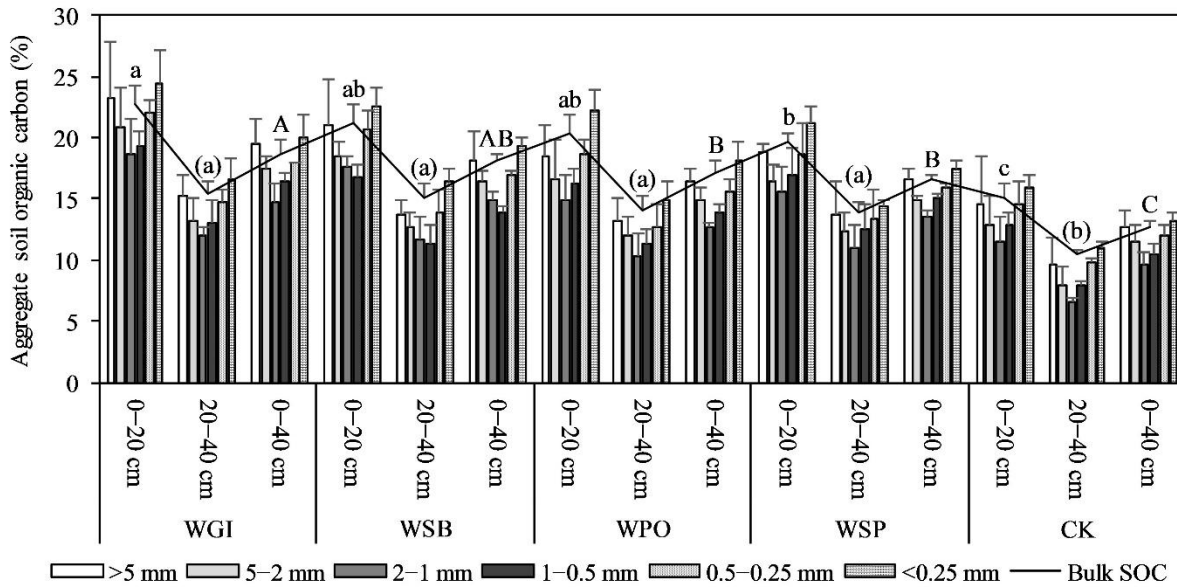


Fig. 6. Aggregate particle-size soil organic carbon (SOC) content among the different intercropping models of walnut plantation. Bars with different letters (lower case for bulk SOC in the 0–20 cm layer; lower case in brackets for bulk SOC in the 20–40 cm layer; upper case for bulk SOC in the 0–40 cm layer) show significant differences at $P < 0.05$.

3.7. Soil nutrient content

WGI showed the highest TN (1.8 g kg⁻¹) in the 0–20 cm layer, significantly ($P < 0.05$) above CK (1.4 g kg⁻¹) (Fig. 7). All intercropping models had similar TN in the 20–40 cm layer, all higher than CK. In the 0–40 cm layer, WGI led with 1.6 g kg⁻¹, followed by WSB, WPO, and WSP, all exceeding CK. AHN was highest in WSB in the 0–20 cm (162.8 mg kg⁻¹) and 20–40 cm (113.2 mg kg⁻¹) layers, significantly ($P < 0.05$) higher than others. The average AHN was highest in WSB (137.1 mg kg⁻¹), followed by WGI, with CK lowest. AVP content in the 0–20 cm layer was highest in WGI (25.4 mg kg⁻¹), WSB (24.3 mg kg⁻¹), and WPO (24.6 mg kg⁻¹), significantly ($P < 0.05$)

above WSP and CK. In the 20–40 cm layer, intercropping models had similar AVP, all above CK. AVP was highest in WGI (18.1 mg kg⁻¹) in the 0–40 cm layer, and lowest in CK. AVK was highest in WGI in the 0–20 cm layer, followed by WPO, WSB, and WSP, with CK lowest. WGI led in the 20–40 cm layer. Overall, WGI had the highest average AVK, and CK the lowest.

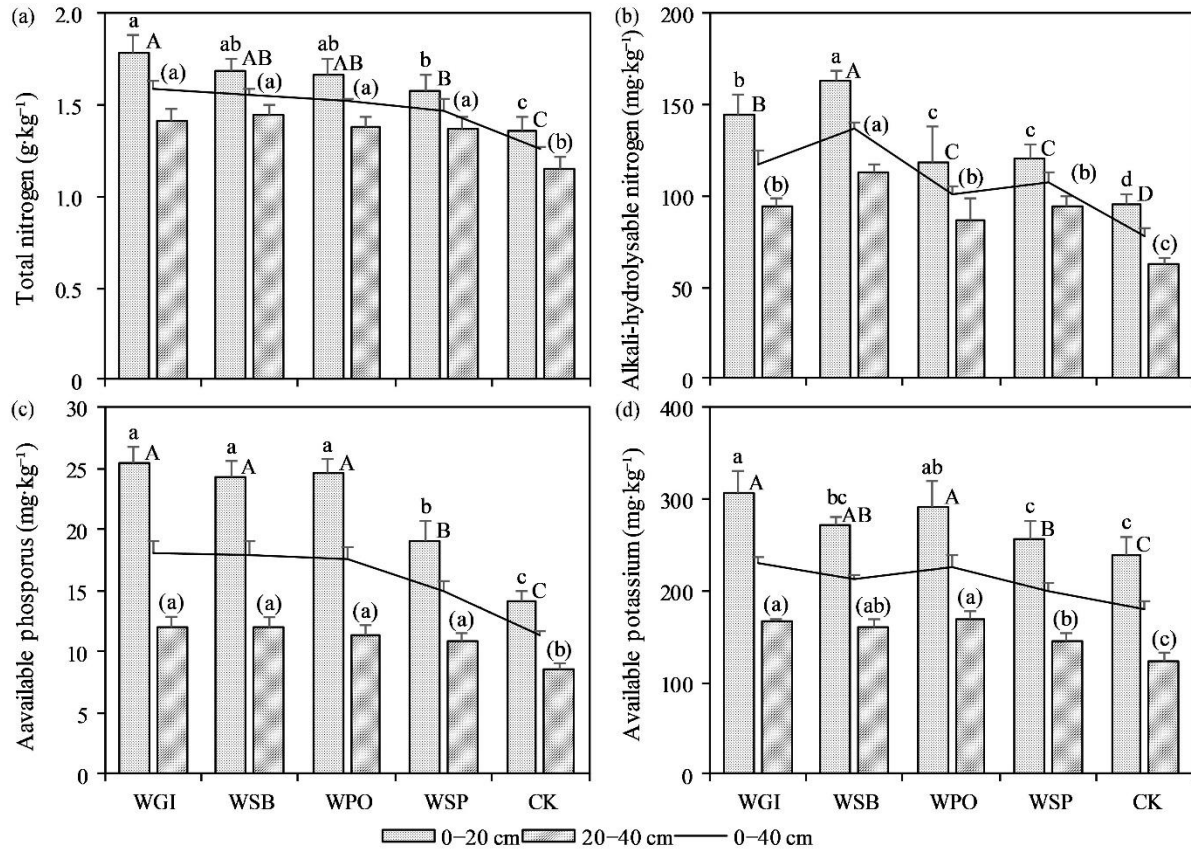


Fig. 7. Soil nutrient content among the different intercropping models of walnut plantation. Bars with different letters (lower case for total nitrogen (TN), alkali-hydrolysable nitrogen (AHN), available phosphorous (AVP), and available potassium (AVK) in the 0–20 cm layer; lower case in brackets for TN, AHN, AVP, and AVK in the 20–40 cm layer; upper case for TN, AHN, AVP, and AVK in the 0–40 cm layer) show significant differences at $P < 0.05$.

3.8. Comprehensive evaluation value

The comprehensive evaluation value (CEV) of soil physical properties and aggregation stability to different intercropping models revealed significant ($P < 0.05$) improvements as compared to the CK. The WGI model has significantly ($P < 0.05$) the best performance among all intercropping models and ranked as WGI (2.94) > WSB (2.72) > WSP (2.18) > WPO (1.83) > CK (0.70). This ranking reflects all intercropping models superior to the CK. The WGI model shows significant ($P < 0.05$) improvements of soil physical properties and aggregation stability. It is important to note that the CEV is a relative ranking index specific to the treatments and site conditions of this study. It should not be interpreted as an absolute measure of soil health or as a universally applicable score.

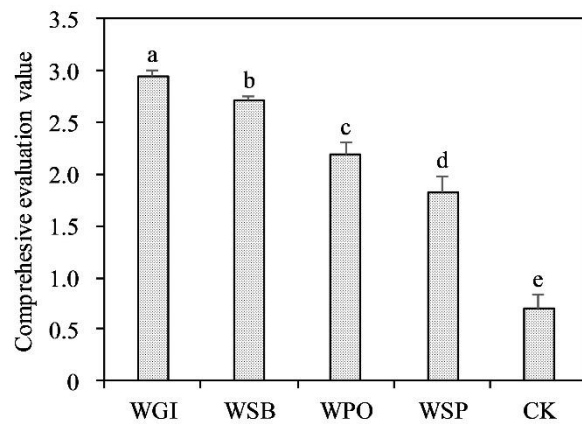


Fig. 8. Comprehensive evaluation value among the different intercropping models of walnut plantation. Bars with different letters show significant differences at $P < 0.05$.

3.9. Correlation analysis

A correlation analysis assessed interactions among the indices (Table 1). Litter stock showed significant ($P < 0.01$) positive correlations with SOC, FRB, and MWD, indicating organic inputs enhance soil structural stability. Litter stock also correlated significantly ($P < 0.05$) positively with total porosity and wet-sieving aggregate proportion >0.25 mm, and significantly ($P < 0.05$ or $P < 0.01$) negatively with bulk density and UAI, suggesting improved soil structure. FRB was

significantly ($P < 0.01$) strongly positively associated with SOC, WSA, and MWD, and significantly ($P < 0.01$) negatively correlated with UAI and FD, showing root biomass promotes aggregate stability. SOC correlated significantly ($P < 0.01$) strongly with MWD and WSA, and significantly ($P < 0.01$) negatively with UAI and FD. MWC and FWC correlated significantly ($P < 0.05$) positively with litter stock and SOC, and significantly ($P < 0.01$) negatively with UAI, highlighting organic enrichment's role in water retention. PCD was significantly ($P < 0.05$ or $P < 0.01$) negatively correlated with litter stock, SOC, and WSA, and significantly ($P < 0.01$) positively correlated with FD, indicating soil degradation inversely relates to organic matter and aggregation stability. CEV significantly ($P < 0.05$ or $P < 0.01$) correlated with SOC, Total N, AHN, AVP, AVK, PCD, UAI, MWD, FD, WSA, bulk density, capillary porosity, NCP, total TP, NWC, MWC, CWC, and FWC.

Table 1 Correlation coefficient of soil physical properties and aggregation stability with chemical properties, litter stock, and fine root biomass

	LS	FRB	SOC	PCD	UAI	MWD	FD	WSA _{>0.25}	BK	TP	CEV
LS	1.00	0.80**	0.82**	-0.64*	-0.79**	0.79**	-0.77**	0.69**	-0.63*	0.53*	0.87**
FRB	0.80**	1.00	0.89**	-0.77**	-0.87**	0.85**	-0.92**	0.85**	-0.63*	0.75**	0.96**
SOC	0.82**	0.89**	1.00	-0.79**	-0.99**	0.94**	-0.88**	0.85**	-0.75**	0.68**	0.94**
TN	0.83**	0.87**	0.89**	-0.68**	-0.86**	0.80**	-0.82**	0.76**	-0.75**	0.72**	0.93**
AHN	0.86**	0.83**	0.79**	-0.61*	-0.76**	0.76**	-0.67**	0.68**	-0.52*	0.55*	0.85**
AVP	0.83**	0.87**	0.85**	-0.57*	-0.83**	0.76**	-0.84**	0.67**	-0.62*	0.84**	0.94**
AVK	0.69**	0.76**	0.75**	-0.52*	-0.72**	0.70**	-0.80**	0.59*	-0.75**	0.73**	0.83**
PCD	-0.64*	-0.77**	-0.79**	1.00	0.77**	-0.81**	0.81**	-0.99**	0.58*	-0.55*	-0.76**
UAI	-0.79**	-0.87**	-0.99**	0.77**	1.00	-0.91**	0.87**	-0.83**	0.73**	-0.67**	-0.91**
MWD	0.79**	0.85**	0.94**	-0.81**	-0.91**	1.00	-0.84**	0.86**	-0.72**	0.64*	0.89**
FD	-0.77**	-0.92**	-0.88**	0.81**	0.87**	-0.84**	1.00	-0.87**	0.79**	-0.78**	-0.93**
WSA	0.69**	0.85**	0.85**	-0.99**	-0.83**	0.86**	-0.87**	1.00	-0.63*	0.63*	0.84**
BK	-0.63*	-0.63*	-0.75**	0.58*	0.73**	-0.72**	0.79**	-0.63*	1.00	-0.55*	-0.70**

CP	0.29	0.55*	0.54*	-0.54*	-0.54*	0.52*	-0.64*	0.59*	-0.46	0.93**	0.64*
NCP	0.76**	0.83**	0.70**	-0.39	-0.69**	0.66**	-0.77**	0.54*	-0.52*	0.79**	0.85**
TP	0.53*	0.75**	0.68**	-0.55*	-0.67**	0.64*	-0.78**	0.63*	-0.55*	1.00	0.82**
NWC	0.33	0.72**	0.61*	-0.73**	-0.60*	0.65**	-0.81**	0.78**	-0.65**	0.78**	0.68**
MWC	0.63*	0.78**	0.79**	-0.64*	-0.77**	0.75**	-0.89**	0.72**	-0.85**	0.91**	0.85**
CWC	0.52*	0.68**	0.73**	-0.65**	-0.71**	0.70**	-0.82**	0.71**	-0.83**	0.87**	0.76**
FWC	0.52*	0.73**	0.73**	-0.73**	-0.72**	0.74**	-0.84**	0.78**	-0.78**	0.89**	0.79**

LS: Litter stock, FRB: Fine root biomass, SOC: Soil organic C, TN: Total N, AHN: Alkali-hydrolysable N, AVP: Available P, AVK: Available K, PCD: Percentage of construction damage, UAI: Unstable aggregate index, MWD: Mean weight diameter, FD: Fractal dimension, WSA_{>0.25}: >0.25 mm wet-sieving aggregate, BK: Bulk density, CP: Capillary porosity, NCP: Non-capillary porosity, TP: Total porosity, NWC: Natural water-holding capacity, MWC: Maximum water-holding capacity, CWC: Capillary water-holding capacity, FWC: Field water-holding capacity. * $P < 0.05$, ** $P < 0.01$.

4. Discussion

4.1. Litter and fine root inputs as drivers of soil physical change

Intercropping significantly increased both litter stock and fine root biomass (FRB) compared to pure walnut, establishing these biological inputs as primary drivers of subsequent soil physical improvements. However, the magnitude depended strongly on the intercrop species. Walnut + soybean (WSB) produced the highest litter stock (1.25 Mg ha⁻¹), whereas walnut + ginger (WGI) had the highest FRB (0.70 Mg ha⁻¹ in the 0–40 cm layer). This reflects fundamental growth habit differences: soybean produces abundant aboveground residue, while ginger develops a dense fibrous root system. The high litter stock in WSB is consistent with Yang et al. (2010). Critically, the strong positive correlation between FRB and SOC ($r^* = 0.76$, $P < 0.01$) suggests a closer association of root-derived carbon with SOC compared to litter, aligning with Liu et al. (2022). This finding provides preliminary evidence that, for the conditions of this study, intercrops with high root biomass may be associated with greater soil carbon benefits.. These increased biological inputs provide the foundation for the physical alterations to soil porosity and water retention discussed below.

4.2. Soil bulk density and porosity

The increased root biomass from intercropping directly translated into reduced bulk density and enhanced soil porosity, though the magnitude varied by crop type. Walnut + ginger (WGI) exhibited the lowest bulk density (1.09 g cm^{-3} in 0–20 cm; 1.31 g cm^{-3} in 20–40 cm) and the highest total porosity (50.8% in 0–40 cm) and capillary porosity (39.7%) among all treatments. These improvements are attributable to the high fine root biomass in WGI, which creates macropores and binds soil particles. Walnut + soybean (WSB) showed the highest non-capillary porosity (11.7%), likely due to soybean taproots creating larger channels upon decomposition. These findings align with previous reports of improved soil physical properties under tree-based intercropping (Chen et al., 2019; Fan et al., 2006; Wang et al., 2022). The strong negative correlation between bulk density and total porosity ($r^* = -0.84$, $P < 0.01$) is consistent with the expected inverse relationship between these variables, while the positive correlation between capillary and total porosity ($r^* = 0.81$) suggests that water-retaining pores are associated with higher overall porosity.. These structural changes directly influenced soil water-holding capacity, as discussed below.

4.3 Soil water-holding capacity

The improved porosity observed in Section 4.2 translated into enhanced water-holding capacity, with WGI showing the greatest increases. Natural water content (NWC) in the 0–40 cm layer increased from 95.8% (CK) to 182.2% (WGI), while maximum water-holding capacity (MWC), capillary water-holding capacity (CWC), and field water-holding capacity (FWC) followed similar patterns. The high fine root biomass in WGI (0.70 Mg ha^{-1}) and its low bulk density (1.20 g cm^{-3} in 0–40 cm) created more pore space for water retention. Ramulu et al. (2017) reported that water-holding capacity increases in tree-crop intercropping due to higher root biomass and organic matter inputs. Sahu et al. (2022) also linked soil porosity and water retention directly to water-holding capacity. Che et al. (2013) demonstrated that water-holding capacity varies with depth and soil

aggregation, consistent with our observation of higher values in the 0–20 cm layer than in 20–40 cm. Positive correlations between NWC, FWC, MWC and both total porosity and FRB (Table 1) are consistent with the interpretation that root-derived organic matter and improved porosity are associated with greater water retention.. These water-retention improvements contributed to enhanced aggregate stability, as discussed in the following section.

4.4 Soil aggregate composition and stability

Increased root-derived organic matter and improved soil moisture conditions jointly promoted the formation of larger macro-aggregates, though the magnitude varied significantly among intercrops (Fig. 4). Large dry aggregates (>5 mm) increased from 26.7% (CK) to 43.6% (WGI), while large water-stable aggregates (>5 mm WSA) increased from 2.5% to 6.6% in the 0–40 cm layer. Correspondingly, the proportion of micro-aggregates (<0.25 mm) decreased, indicating a shift toward a more aggregated and erosion-resistant soil structure. These improvements are attributed to higher SOC and fine root biomass under intercropping. Chen et al. (2017) reported that litter fall and extensive root systems in agroforestry enhance SOC and improve soil aggregation. Lehmann et al. (2017) also noted that soil biota and organic matter act as binding agents. These compositional changes directly influenced aggregate stability indices, as discussed in Section 4.5

4.5. Soil aggregate stability and fractal dimension

The enhanced formation of macro-aggregates translated into improved aggregate stability, as reflected by higher mean weight diameter (MWD), lower fractal dimension (FD), and reduced structural damage (Fig. 5). Mean weight diameter (MWD) increased from 1.63 mm (CK) to 2.51 mm (WGI), while fractal dimension (FD) decreased from 2.93 to 2.86, indicating a more stable and complex soil structure. Percentage of structural damage (PCD) and unstable aggregate index (UAI) also decreased significantly, with WGI exhibiting the lowest values. These results are consistent with Zhang et al. (2022), who demonstrated that intercropping significantly improves

large soil aggregates. The negative correlation between PCD and wet-sieved aggregate proportion ($r^* = -0.99$, $P < 0.01$) and the positive correlation between PCD and FD ($r^* = 0.81$, $P < 0.01$) are consistent with the interpretation that lower aggregate fragmentation is associated with higher stability.. The relationship between aggregate stability and SOC content is explored in Section 4.6.

4.6. Aggregate particle-size soil organic carbon

Intercropping increased SOC content across all aggregate size classes, with the greatest accumulation in macro-aggregates (Fig. 6). In the 0–40 cm layer, SOC in >5 mm aggregates was highest in WGI (19.5 g kg⁻¹) and lowest in CK (12.6 g kg⁻¹). Bulk SOC followed the same trend (WGI: 18.7 g kg⁻¹; CK: 12.7 g kg⁻¹). This pattern supports aggregate hierarchy theory, which posits that SOC accumulates first in macro-aggregates, which then help stabilize micro-aggregates (Chen et al., 2017).

Critically, SOC across aggregate size classes exhibited a "V-shaped" distribution: decreasing from >5 mm to 2–5 mm, then increasing in the <0.25 mm fraction. We propose this pattern reflects distinct carbon stabilization mechanisms at opposite ends of the aggregate size spectrum. In macro-aggregates (>5 mm), high SOC is driven by physical entrapment of fresh, labile plant debris (roots and litter) within large pore spaces, where decomposition is limited by oxygen diffusion and physical protection (Six et al., 2004). In contrast, elevated SOC in micro-aggregates (<0.25 mm) likely represents old, recalcitrant organic matter chemically stabilized through mineral association (von Lützow et al., 2007). The intermediate 2–5 mm fraction may represent a transitional zone where fresh organic matter actively decomposes before incorporation into stable micro-aggregates, resulting in lower SOC. This mechanism has direct management implications: intercrops like ginger, which promote root-derived carbon inputs and macro-aggregate formation, may contribute to fresh carbon transfer into protected pools, potentially supporting long-term soil carbon

sequestration. However, further research is needed to confirm this causal pathway.. The relationships between SOC, aggregate stability, and nutrients are explored next.

4.7. Soil nutrient content

The SOC accumulation observed in Section 4.6 was accompanied by corresponding increases in soil nutrients, though the magnitude varied by crop type and nutrient element. Walnut + ginger (WGI) showed the highest total nitrogen (TN: 1.8 g kg⁻¹ in 0–20 cm), available phosphorus (AVP: 25.4 mg kg⁻¹), and available potassium (AVK). Walnut + soybean (WSB) excelled in alkali-hydrolysable nitrogen (AHN: 137.1 mg kg⁻¹ average), likely due to biological nitrogen fixation (Dai et al., 2019). Similar increases in TN under agroforestry were reported by Lian et al. (2019) and Cardinael et al. (2018). The positive correlations between SOC and both MWD and WSA (Table 1) are consistent with the interpretation that higher organic matter is associated with improved nutrient retention, as stable aggregates protect organic matter from rapid mineralization (Chen et al., 2017). The comprehensive evaluation value (CEV) ranking (WGI > WSB > WSP > WPO > CK) further supports WGI as the best performing model for overall soil quality enhancement, though WSB may be preferred when nitrogen improvement is the primary management objective. These differential responses among intercrop species are synthesized in the following section.

4.8. Differential crop performance: A functional trait comparison

The four intercrops exhibited distinct effects, reflecting differences in functional traits. Walnut + ginger (WGI) outperformed all others due to its dense fibrous root system (0.70 Mg ha⁻¹ FRB), enhancing SOC, porosity, and aggregation without soil disturbance. Walnut + soybean (WSB) ranked second, excelling in litter production (1.25 Mg ha⁻¹), non-capillary porosity (11.7%), and nitrogen fixation (Dai et al., 2019). Walnut + sweet potato (WSP) and walnut + potato (WPO) showed moderate improvements, with WSP slightly outperforming WPO in the comprehensive

evaluation (CEV ranking: WGI > WSB > WSP > WPO > CK). WSP's moderate performance reflects its tuberous root system and limited root exudates, while WPO's performance was limited by tuber harvesting disturbance. These results indicate that species selection must consider both aboveground and belowground traits. The practical implications are discussed below.

4.9. Management implications and study limitations

Our findings demonstrate that intercropping with ginger (WGI) is highly effective for improving soil physical properties in young walnut plantations. From a management perspective: (1) ginger may be a suitable choice for soil rehabilitation and carbon sequestration; (2) soybean could be considered as a viable alternative when nitrogen improvement is the primary goal; and (3) sweet potato provided minimal benefits compared to the other intercrops tested. These findings are specific to young stands (age 6) in a subtropical monsoon region; validation across broader geographic areas, soil types, and stand ages is needed. Similarly, the CEV ranking is site-specific and should be interpreted as a relative comparison among the treatments tested, rather than an absolute or transferable soil quality score. Additionally, while correlation analyses revealed strong associations among soil properties, these relationships should not be interpreted as causal, as soil physical, chemical, and biological properties are inherently interdependent. Despite this limitation, the study provides a scientific basis for selecting intercrops to optimize soil health in walnut-based agroforestry systems.

5. Conclusion

Under the edaphoclimatic conditions of this study, intercropping with ginger (WGI) significantly improved soil physical properties, water retention, and aggregate stability in young walnut plantations, outperforming soybean, potato, and sweet potato. A novel finding was the "V-shaped" distribution of SOC across aggregate size classes, with distinct stabilization mechanisms operating in macro- (>5 mm) and micro- (<0.25 mm) aggregates. The strong correlation between fine root

biomass and SOC suggests that root-derived inputs are closely associated with soil structure improvement.

From a management perspective, ginger may be suitable for soil rehabilitation and carbon sequestration in similar agroecological settings, while soybean could be considered when nitrogen improvement is the primary objective. Sweet potato provided minimal soil benefits compared to the other intercrops tested.

These findings provide a scientific basis for selecting intercrops in walnut-based agroforestry systems under subtropical monsoon climates. However, the CEV approach and the specific rankings reported here should be validated under different edaphoclimatic conditions, soil types, and stand ages. Therefore, the recommendations presented here should be considered preliminary and site-specific.

• Abbreviations

Not applicable.

• Ethics approval and consent to participate

Not applicable.

• Consent for publication

All authors consent to publish the article.

• Availability of data and materials

All datasets generated for this study are included in the article.

• Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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● Authors' contributions

Wei Gong and Jingyan Wang have supervised related experiments and revised the manuscript. Muhammad Asghar Ali, Jinri Xue, Weiyi Yang, Xiulin Zhu, Fozia Dost Muhammad, and Qi Lu performed the experiments. Muhammad Asghar Ali compiled the data and wrote the manuscript. Fozia Dost Muhammad and Shuaijie Lu revised the manuscript. All authors have read and approved the manuscript.

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